15 Apr 2004, 7:00pm - 8:30pm

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

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ABSTRACT

It is generally accepted, that only chemical grouts or solutions are available to penetrate and fill narrow joints or soils with very small pore size. During the last 30 years, a few hundreds of different compounds have been used for this purpose. Such materials show a wide spectrum of properties. Epoxy resins are some of the common compounds which are used in chemical grouting due to their high strength and durability against mechanical or physical erosion. In this paper, the improvement of physical and mechanical properties of fine sand injected with a water soluble, two component epoxy resin is investigated. The experiments were carried out, either using only epoxy resin("one shot process") or, in combination with sodium silicate("two shot process"). For this reason, two epoxy resin solutions have been employed. The one was thick with water/resin (W/R) ratio of 1 and the other was more dilute with W/R of 2. The grouting was performed through 10 cm diameter columns, filled with siliceous sand with particle size distribution of 0.149/2.1mm and 0.076/2.1mm. For the two shot grouting, two solutions of sodium silicate were used, with sodium silicate/water ratio of 3 and 2, respectively. Results of a comparison between the above two processes, showed that the compressive strength and durability of injected sand specimens of the one shot process is much lower than that of the two shot process. On the contrary, the permeability and the porosity of the sand were lowered much more in the first case.

INTRODUCTION

Grouting is a ground modification system used to create in situ cemented geometries and properties of soil. Grouts comprise several constituents which are combined in many ways, according to in situ conditions and the outcome desired each time (Nonveiller, 1989). The major component of hydraulic hardening grout is a cement suspension and of chemical grout are epoxy resins or solutions. The most suitable grouting material fulfils the following requirements (Widmann, 1996):

- To penetrate easily into the soil pores
- To reach a large radius with low pressure
- To fill the voids completely
- To maintain the required properties in the hardened state
- To improve durability of grouted soil (Baker, 1982, Baker et al, 1983)

Cement grouts are used successfully in soils with penetrability greater than 10^{-2} m/sec (Cambefort, 1964), or in fractured rock with wide crack openings, because they meet the above requirements, whereas their cost is far lower than that of chemical grouts. As a result, the use of chemical grouts, and especially of synthetic resins, are restricted to soils with very small void size or rock mass with narrow joints, where cement suspensions can not be injectable or their penetration is very limited (Perret et al., 2000).

A multitude of materials is represented under the heading of synthetic resins. Synthetic resins are organic agents which are either fluid and fusible or soluble (Karol, 1960). They cure by polyaddition, polymerization or polycondensation to a resin, either by self-reaction or by action of hardening agents, accelerators or others (Vik et al, 2000). Besides unsaturated polyesters, only epoxy and polyourethane resins are used without solvents and inert plasticizers. Materials, such as silica fume, calcium carbonate or barium sulphate can generally be used as mineral fillers. Epoxy resins are characterized by high strength in compression and bonding, even on wet surfaces.

In this work, is explored the variation of physical (water permeability, porosity, dry unit weight), mechanical (compressive strength, elastic modulus) characteristics and durability of injected fine sand specimens with two-component water soluble epoxy resin. A series of tests were conducted to investigate the influence of particle size distribution, the water/resin(W/R) ratio, the sodium silicate(S.S) as an accelerator and the distance from the grouting point on the improvement of sand characteristics.

MATERIALS

Sand specimens

Injection tests were carried out on two types of siliceous river

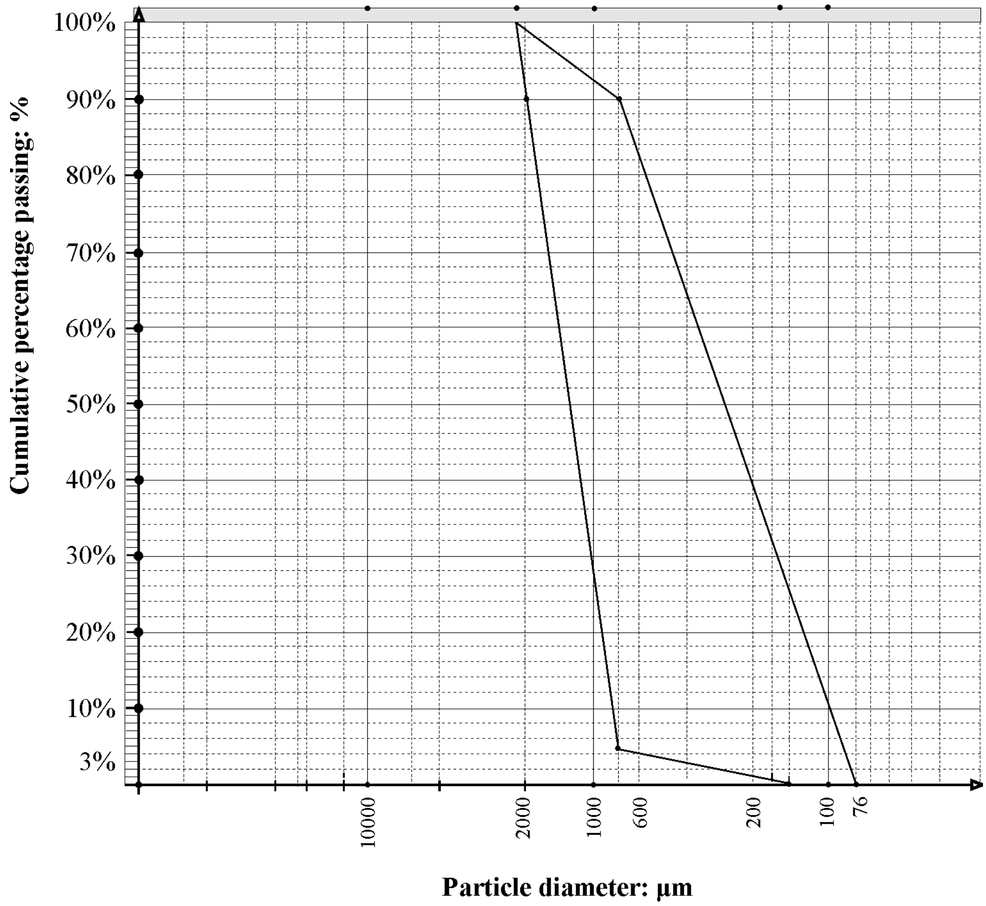

Fig. 1. Grain size distribution of the sands.

Table 1. Properties of sand used for injection tests

Particle-size distribution: mm	Degree of saturation: %	Water content of soil: %	Dry unit weight of soil: t/m^3	Saturated unit weight: t/m^3	Porosity: %	Water permeability: m/s
0,149/2,1	98	28	1,55	1,98	0,43	10^{-2}
0,076/2,1	95,8	25	1,62	2,03	0,40	$1{,}42\cdot10^{-4}$

sand. The sands had particle-size distribution of 0.149/ 2.1mm and 0.076/2.1mm and are referred to here as coarser and finer sands respectively (Fig.1). The properties of the two types of sand are shown in Table 1.

<u>Sodium Silicate</u>

Sodium silicate (S.S) used for two-shot grouting had molecular ratio of SiO_2 / Na_2O equal to 3.Two S.S solutions were employed, having an S.S / Water ratio of 3 and 2, respectively.

<u>Epoxy Resin</u>

The epoxy resin used was water-soluble, and comprised two components. The mixture ratio by weight of the two components A (epoxy resin) and B (hardener) was 0.5. For the injection tests, two epoxy resin solutions were used, with W/R ratios of 1 and 2 respectively.

LABORATORY PROCEDURE

The test program involved 24 permeation groutings on columns filled with fine and coarse sand fractions, with epoxy resin and sodium silicate grouts of various ratios, in respect to water, in one shot and two shot processes. From 12 of injected sand columns, were taken specimens for the compression tests, whereas from the rest columns, the specimens were used for the estimation of slake durability, dry unit weight, porosity and water permeability. The composition and the various

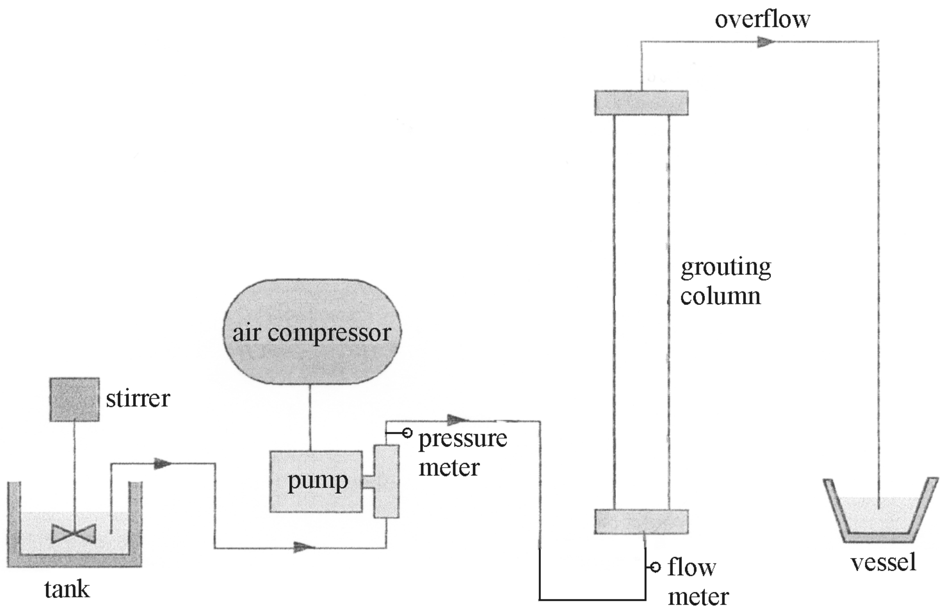

Fig. 2. Apparatus for grouting sand columns.

combinations of the grouts used, was the following:

- W/R=1 one shot process
- W/R=2 " " "
- W/R=1 + S.S/W=2 two shot process
- W/R=1 + S.S/W=3 " " "
- W/R=2 + S.S/W=2 " " "
- W/R=2 + S.S/W=3 " " "

The experimental setup used for the injections, was constructed according to A.S.T.M D4320-93 specifications and comprised the following parts (Fig.2):

- Mixing tank with a high speed rotating stirrer
- Air operated double diaphragm pump
- Air compressor
- Pressure and flow meters
- The grouting column. It was a two piece split metallic tube, with diameter of 10 cm and length of 150 cm, to facilitate sample removal .
- Vessel for the collection of grouts which come out from the tube.

Sodium silicate and epoxy resin grouts were prepared in batches of 10 l and mixed for 5 min at least. Injection tests in one shot process were carried out with low pressure, about 100 KPa, due to the fact that epoxy resin grouts exhibited good fluidity and low plastic viscosity (Snuparek and Soucek, 2000). Flow rate was 0.1 l /sec. Injection was stopped, when the excess grout equivalent to 120 % of the sand pore volume had passed through the sample (Mollamahmutoglu and Littlejohn, 1997). In the two shot process case, the sand specimens were left to drain out from the excess of epoxy resin grout, by opening the bottom of the column, and consequently, were injected with sodium silicate grout.
Special precautions were taken to the injection pressure of the sodium silicate solutions. Due to the fact, that their viscosity is higher than the corresponding of epoxy resin, the epoxy resin could have been leached out, if the injection pressure of sodium silicate grout was high. Also, it was not possible to apply very low pressure, because the immediate conversion of epoxy resin from water-soluble form in gel-form, due to its contact with the sodium silicate solution, could form an impermeable layer, near the grouting point. This may be attributed to the transportation of some flocs of epoxy resin and their accumulation along with other flocs, in a domain, where due to the fact that the pressure is low, sodium silicate could not surpass this obstacle.

For all the above reasons, it was decided that the initial injection pressure of sodium silicate grouting to be 50 KPa and it was slightly increasing, in order the flow rate to remain almost constant. The injection was stopped, when an amount of sodium silicate started to exit from the outlet of the column.
The grouted sands were left in the molds for a day and then demolded and cut into lengths of 20 cm. After that, they were sealed in plastic bags and stored in a 100 % relative humidity curing room, until the time of testing.

Cylindrical specimens of 10 cm diameter and 20 cm height, were used for compression tests (A.S.T.M. C 109).All tests were performed under a constant strain rate of 0.1 % / min (Ata and Vipulanandan, 1999).Specimens of the same size were used for the estimation of porosity, water absorption, dry unit weight (A.S.T.M. C 97-83) and water permeability (A.S.T.M. D 5084). Development of strength was evaluated from the compression tests at the age of 28 days.

The slake-durability test was developed by Franklin (Franklin and Chandra, 1972) and used to predict the potential deterioration of durability due to climatic wetting and drying. Also this test contributes to the improvement of engineering properties

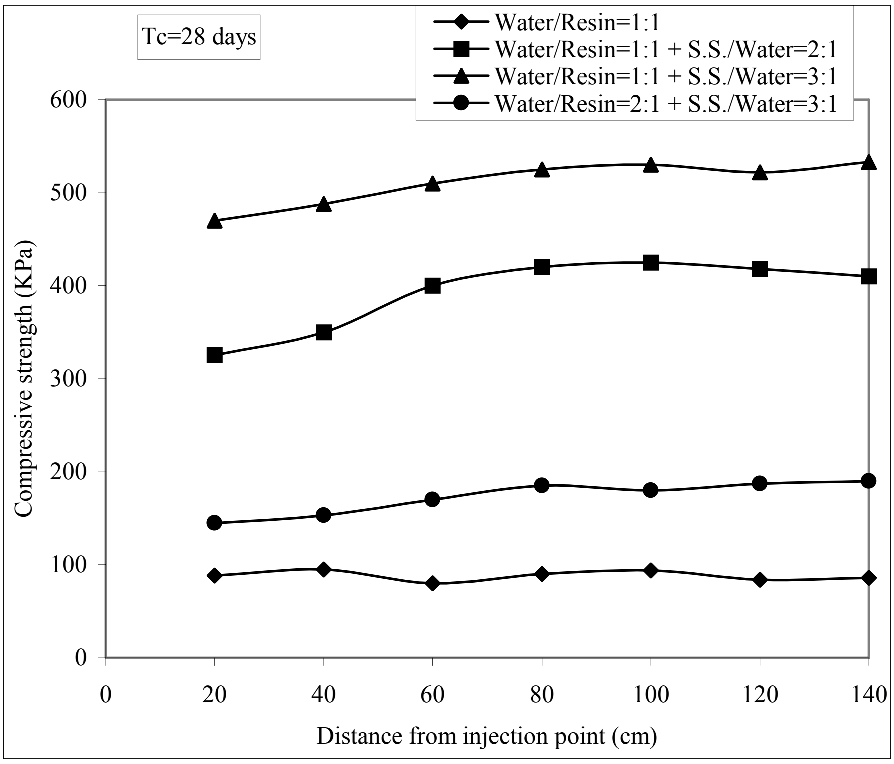

Fig. 3. Compressive strength of injected coarser sand specimens of one and two shot processes vs. the distance from the grouting point in 28 days.

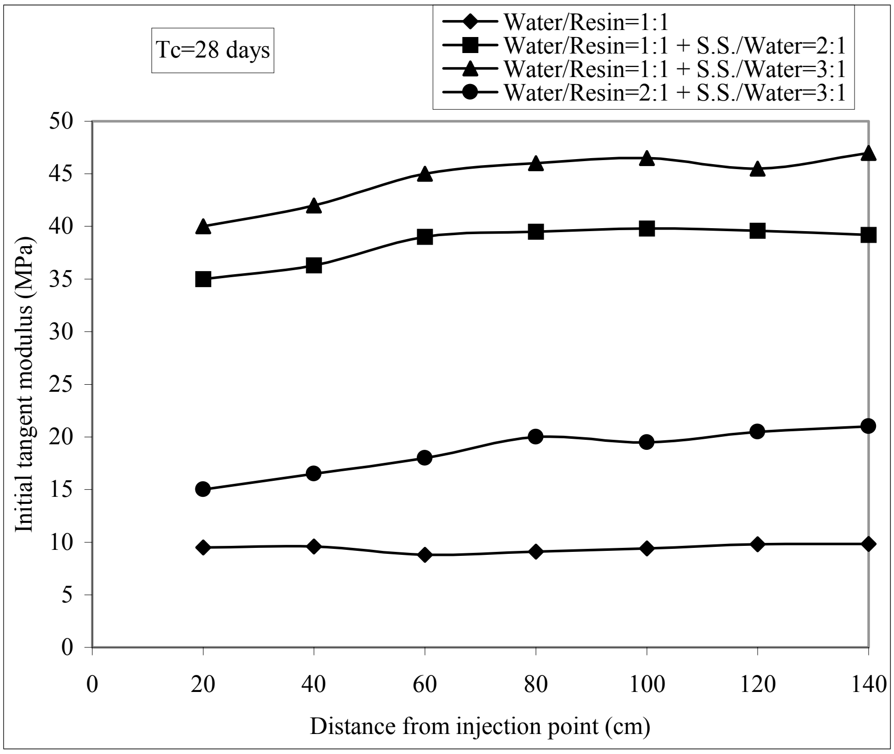

Fig. 4. Initial tangent modulus of injected coarser sand specimens of one and two shot processes vs. the distance from the grouting point in 28 days.

of a soil by relating the grouting parameters (composition and combinations of grouts, grain size, porosity, days of curing) with the potential bonds developed between soil grains during grouting by epoxy resin and sodium silicate.

The slaking (100 – Id_2) was measured using the device and testing procedure developed by Franklin.

Finally, the slake durability index (Id_2-second cycle) was calculated as the percentage ratio of the final to initial dry sample weight.

RESULTS AND DISCUSSION

No strength development was observed, even after 28 days, in the case of epoxy resin grouting with W/R=2 in coarser sand. Injected finer sand with the same grout has not exhibited any appreciable strength in 3 and 7 days, but in 28 days the strength values had slight fluctuation in relation to the distance from the grouting point (Fig.5,6). These values were in the range of 950-1100 KPa, whereas the elastic modulus was fluctuated from 38 to 42 MPa. This was an indication of a permeation of the sand grains by the grout in an equal extent. The water permeability, porosity and dry unit weight of every part taken from the injected column, had values similar to the mean values 10^{-5} m/sec, 30% and 1.65gr/cm^3 respectively.

In the case of epoxy resin grouting with W/R=1 in coarser sands, the strength was generally low (80-95 KPa), despite the high resin content in the grout, whereas the elastic modulus was from 8.8 to 9.85 MPa (Fig.3,4). Nevertheless, the porosity was lowered significantly, as well as the permeability, with mean values of 24% and 6.10^{-4} m/sec correspondingly, whereas the increase of dry unit weight was low, with a mean value of 1.6 gr/cm^3.

In 28 days, the strength of injected finer sand was fluctuated from 1150 to 1260 KPa. Porosity and permeability were lowered substantially and were 20 % and $5.7.10^{-7}$ m/sec respectively, whereas the dry unit weight was 1.7 gr/cm^3 .

Experiments of one shot process showed that the setting time of the injected sand was very high, whereas the strength was not too high. This may be attributed to the amount of water, which is detained by the hydrophilic parts of epoxy resin, inhibiting in some extent its reaction with the hardener, and thus, the development of strength.

In an effort to overcome these adverse effects, additional injections of sodium silicate (S.S) have been carried out, after the injection of sand specimens with epoxy resin grout. In a sodium silicate aqueous solution, the Na^+ ions are being attracted by the negatively charged hydrophilic groups of epoxy resin, resulting in resin flocculation and in this way, its separation from the aqueous phase. Through this mechanism, the resin-hardener reaction is accelerated, resulting in a strength enhancement.

Injection of a solution with S.S/W ratio of 2 in grouted coarser sands with W/R=1, resulted significantly to strength development. The average increase of the strength was 445 % and of the elastic modulus was 406 % , in relation to the corresponding results from the one shot process.

Injection of a solution with S.S/W=3, improved these properties even further. In 28 days, the compressive strength and elastic modulus exhibited mean values of 511 KPa and 44.6 MPa.

There wasn't any strength development, for 28 days, after injection of a solution with S.S/W=2 in grouted coarser sands with W/R=2. Besides, injection of a thicker solution, having S.S/W=3, resulted in 28 days strength of 145-190 KPa, and the elastic modulus of 15-21 MPa.

Inspecting the diagrams depicting the variation of the compressive strength and the elastic modulus in relation to the distance from the grouting point, a very significant effect was observed:

As far as the distance from the grouting point increases, the compressive strength and elastic modulus of the two shot process injected specimens exhibit an increasing tendency as well. This may be attributed to the partial leaching of the amount of the epoxy resin, which was trapped in the grains of the first part of the sand column specimen and in this way, its transportation to the next parts of the column.

This effect was much more intense in case of finer sand specimens. Injection of a solution with S.S/W=2 in grouted finer sand with W/R=1, has improved the strength and the elastic modulus very much. For the first three parts of the column were 3590 KPa and 224 MPa, whereas for the rest four parts were 5460 KPa and 263 MPa respectively. Injection of a solution with S.S/W=3, increased the mechanical properties even further. Also significant improvement of the strength was observed after the sodium silicate solutions grouting in injected finer sands with W/R=2.

Although the strength of the injected sand, and especially the finer one, was very high, due to sodium silicate injection, the porosity and permeability were surprisingly high (Tables 2,3), whereas the dry unit weight retained values, similar to the corresponding of the one shot process.This should be attributed to the flocculation and shrinkage of the macromolecular chains of the epoxy resin. As a result, the rigid grid which was formed around the sand grains, had lower volume in the voids of the sand specimens.

The coarser sand is more susceptible to breakdown. The reason is that the greater the grain size, the greater is the contact area and the required amount of grout to develop strong bonds for enough strength and durability (Stavridakis, 1997). The coarser sand specimens of 28 days curing for one and two shot process were disintegrated (100% slaking).

The results of slake durability test in 28 days of curing for injected finer sand specimens are shown in Fig.7. The effect of S.S. solution in finer sand specimens of the above grouting

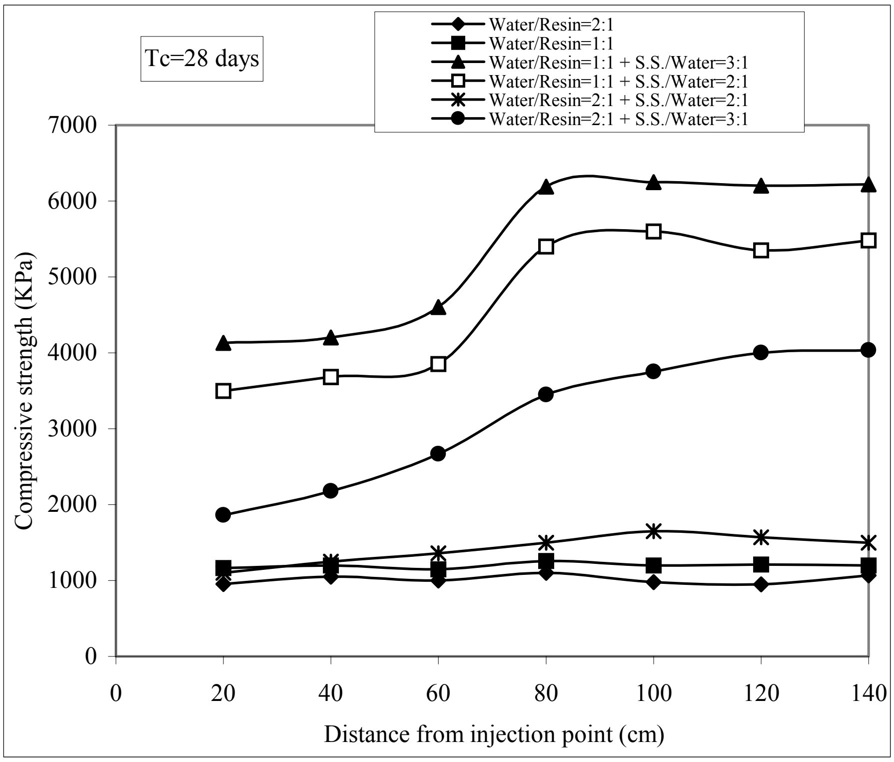

Fig. 5. Compressive strength of injected finer sand specimens of one and two shot processes vs. the distance from the grouting point in 28 days.

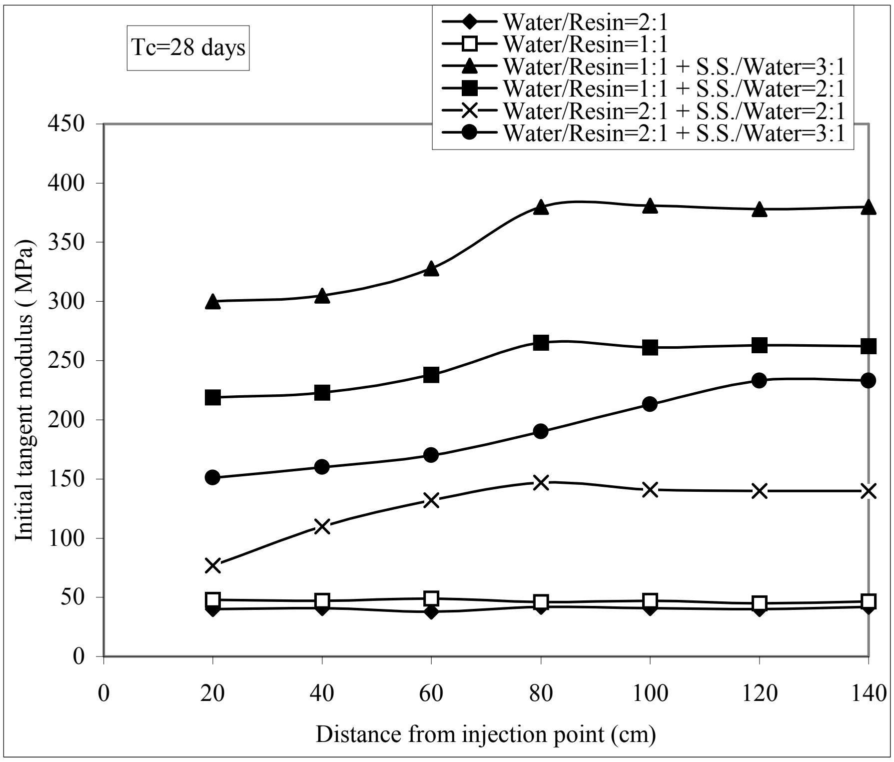

Fig. 6. Initial tangent modulus of injected finer sand specimens of one and two shot processes vs. the distance from the grouting point in 28 days.

Table 2. In situ properties of injected coarser sand with two shot process

Properties	Combination			Distance from grouting point (cm)
	W/R=2+S.S./W=3	W/R=1+S.S./W=2	W/R=1+S.S./W=3	
Water permeability (m/sec)	$8{,}3\cdot10^{-3}$	$1{,}4\cdot10^{-3}$	$2{,}3\cdot10^{-3}$	0-40
Porosity (%)	39,5	34,2	361	
Dry unit weight (gr/cm^3)	1,56	1,58	1,57	
Water permeability (m/sec)	$7{,}6\cdot10^{-3}$	$1{,}05\cdot10^{-3}$	$0{,}95\ 10^{-3}$	40-80
Porosity (%)	36,6	31,5	30,3	
Dry unit weight (gr/cm^3)	1,575	1,588	1,591	
Water permeability (m/sec)	$7{,}2\cdot10^{-3}$	$0{,}85\cdot10^{-3}$	$0{,}78\cdot10^{-3}$	80-120
Porosity (%)	35,1	29,2	27,9	
Dry unit weight (gr/cm^3)	1,587	1,6	1,62	

Table 3. In situ properties of injected finer sand with two shot process

Properties	Combination				Distance from grouting point (cm)
	W/R=2+S.S./W=2	W/R=2+S.S./W=3	W/R=1+S.S./W=2	W/R=1+S.S./W=3	
Water permeability (m/sec)	$8{,}1\cdot10^{-5}$	$8{,}75\cdot10^{-5}$	$2{,}9\cdot10^{-5}$	$4{,}3\cdot10^{-5}$	0-40
Porosity (%)	36,5	38,1	32	34	
Dry unit weight (gr/cm^3)	1,63	1,632	1,68	1,682	
Water permeability (m/sec)	$6{,}8\cdot10^{-5}$	$6{,}3\cdot10^{-5}$	$2{,}6\cdot10^{-5}$	$2{,}85\cdot10^{-5}$	40-80
Porosity (%)	35	35,6	31,5	32	
Dry unit weight (gr/cm^3)	1,64	1,637	1,695	1,684	
Water permeability (m/sec)	$5{,}7\cdot10^{-5}$	$5{,}2\cdot10^{-5}$	$1{,}87\cdot10^{-5}$	$1{,}5\cdot10^{-5}$	80-120
Porosity (%)	32,3	31	28,3	27	
Dry unit weight (gr/cm^3)	1,648	1,66	1,71	1,72	

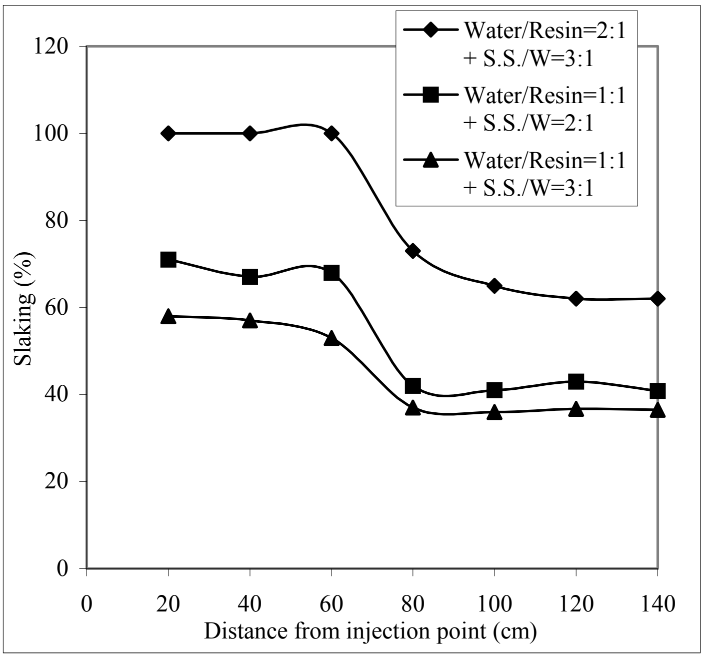

Fig.7. Slaking (%), durability of injected finer sand specimens of two shot process vs. the distance from the grouting point in 28 days of curing.

processes is more obvious. The greater is the density of injected S.S. solution, the greater is the durability.

The effect of distance from the grouting point on durability is shown in Fig.7. As far as the distance from the grouting point increases, the durability also increases.

CONCLUSIONS

Based on the experimental results, the following conclusions can be made:

a) From the experimental results it was shown that the efficiency of the one shot and two shot process, depends directly upon the grain size. The finer is the sand, the greater is the improvement observed of its physical and mechanical properties.
b) Lower W/R ratios have as a result higher strength and durability and lower porosity and water permeability of the injected specimens.
c) The strength and durability increase is influenced by the sodium silicate solution density. Porosity and water permeability didn't show the same improvement, as observed in the one shot process, due to the shrinkage of the epoxy resin macromolecular chains.
d) It can be concluded that injection of epoxy resin grouts is the method of choice, in case of water inlet/outlet limitation purposes, by lowering the soil permeability. The two shot process method should be applied, when the increase of the soil strength and durability (Tables 2,3) is the main target (e.g. in foundations).

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